The rocky road from research to operations for satellite ocean-colour data in fishery management

Cara Wilson*

Environmental Research Division, NOAA Southwest Fisheries Science Center, 1352 Lighthouse Ave., Pacific Grove, CA 93950, USA

Corresponding Author: tel: +1 831 648 5337; fax: +1 831 648 8440; e-mail: cara.wilson@noaa.gov.

The aim of the SAFARI project is to accelerate the assimilation of earth-observation data into fisheries research and management by facilitating the application of rapidly evolving satellite technology. This assumes that these data will be available in future. However, for ocean-colour data, that assumption may not hold because of possible gaps in data continuity. Of the many types of satellite data, ocean colour is the most important to fisheries, because it is the only biological measurement. However, current ocean-colour sensors are all operating beyond their planned design life, and there are potential problems with future launches. Although the research community is aware of the value of satellite ocean-colour data, advocacy from the operational community, fishery management in particular, has been lacking. In the United States, the absence of an easily identifiable operational need for ocean-colour data is largely responsible for the likely gap in data continuity. A range of current and potential operational uses of ocean-colour data, some reasons why these data have been underutilized in fishery management, and what can be done to mitigate them are discussed and outlined.

Keywords: chlorophyll, fisheries, research to operations, satellite ocean colour.

Introduction

Environmental satellite data measurements, such as sea surface temperature (SST), sea surface height, ocean colour, and surface vector winds, are valuable resources needed to understand, monitor, and predict changes in the earth's ecosystems, climate, and weather. In the United States, the two agencies responsible for flying environmental satellites are the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA). NASA is responsible for research and development of new satellite missions, whereas NOAA is responsible for launching and maintaining operational satellites to acquire data on the earth's atmosphere and oceans and providing continuity for these datastreams. However, little of the sensor technology developed by NASA has been utilized by NOAA (National Research Council, 2003; US Commission on Ocean Policy, 2004). The transition process from research to operations (R2O) has earned the nickname "valley of death", a metaphor for the barriers separating research results from operational applications (National Research Council, 2000a). This "valley of death" has been bridged fairly successfully for weather forecasting (Serafin et al., 2002) and discussion has started about the R2O process for climate issues (National Research Council, 2000b, c). The altimetry community has successfully lobbied for continued implementation, using the simple message that sea surface height measurements are imperative for monitoring global sea-level rise (Cazenave and Llovel, 2010). However, there has been little discussion of R2O for ocean-colour data or for applications related to ecosystems and fishery management. The absence of clearly defined operational needs for ocean-colour

data is problematic, because the justification for launching operational satellite missions requires them.

Here, a brief summary of past, current, and scheduled ocean-colour sensors, from the United States and other countries, is given along with an overview of the research that has developed because of the availability of ocean-colour data. After describing the term operational, a range of current and potential "operational" uses of ocean-colour data is discussed. Some reasons why ocean-colour data have been underutilized in fishery management and what can be done to mitigate them are outlined. The United States is not the only country flying ocean-colour satellites: Europe, Japan, and India all have satellite ocean-colour programmes, but the focus here is on the R2O process of ocean colour in the United States. Hence, operational usages of ocean-colour data are discussed from a US perspective, an important caveat, because there are international differences in what constitutes operational usage.

The history of satellite ocean colour

The first ocean-colour satellite, the Coastal Zone Color Scanner (CZCS), was launched in 1978 by NASA, and was operational until late 1986 (Figure 1). CZCS was a "proof-of-concept" mission, intended to last just 1 year, which demonstrated that satellite ocean-colour measurements could be used reliably to derive products such as chlorophyll a and sediment concentrations (Barale and Schlittenhardt, 1993; Mitchell, 1994). Most importantly, it provided justification for subsequent ocean-colour missions, such as the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging

Spectroradiometer (MODIS) in the United States, although there was a ten-year gap between CZCS and the launch of SeaWiFS in 1997 (Figure 1). SeaWiFS and MODIS were both launched by NASA as research missions. Two MODIS sensors were launched, one on the Terra satellite in 1999 and one on the Aqua satellite in 2002. However, because of uncertainties and instabilities in the pre-launch and in-orbit characterization of MODIS-Terra, these data have been largely unusable (Franz et al., 2008). Hereafter, the term "MODIS" refers to the sensor on the Aqua satellite. Although SeaWiFS was still operating in 2010, there have been problems with its telemetry since January 2008, resulting in intermittent data gaps.
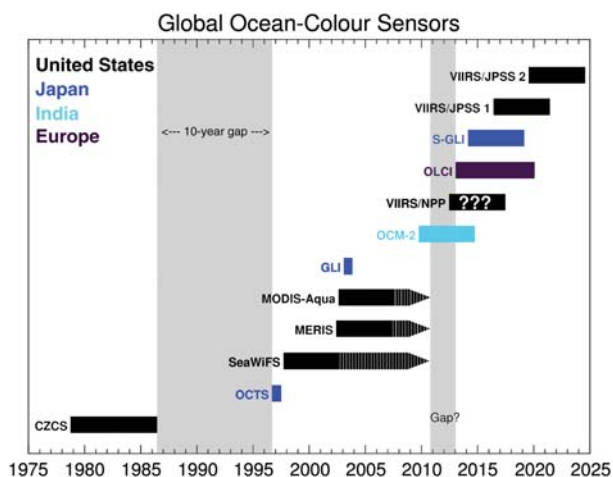
Figure 1. Time-line illustrating past, current, and future global ocean-colour satellite missions. Satellites still generating data are displayed as arrows, and hashed areas indicate the period when the current sensors have passed their 5-year design life. Grey-shaded areas indicate the past and potential future gap in ocean-colour data. CZCS, Coastal Zone Colour Scanner; OCTS, Ocean-Colour Temperature Scanner; SeaWiFS, Sea-viewing Wide Field-of-view Sensor; OCM, Ocean Colour Monitor; MERIS, Medium Resolution Imaging Spectrometer; MODIS, Moderate Resolution Imaging Spectroradiometer; GLI, Global Imager; VIIRS, Visible Infrared Imager Radiometer Suite; NPP, NPOESS Preparatory Project (NPOESS: National Polar-orbiting Operational Environmental Satellite System, now restructured into JPSS); OLCI, Ocean Land Colour Instrument; S-GLI, Second-Generation Global Imager; JPSS, Joint Polar Satellite System.

Other countries have also developed ocean-colour programmes. Japan launched two ocean-colour sensors, the Ocean-Colour Temperature Scanner (OCTS) in 1996 and the Global Imager (GLI) in 2002. Neither remained operational for more than a year (Figure 1).

India launched the Ocean-Colour Monitor (OCM) in 1999. However, data from this sensor have generally not been available to the international community and there are also serious issues with its calibration (Lyon, 2009). The inaccessibility of these data is evident from the small number of papers citing OCM (65, see Table 1) relative to SeaWiFS (1175), despite their similar time in orbit (Figure 1). Most papers using OCM data have come from the Indian community (Figure 2), which underscores the inaccessibility of the data on an international level. The numbers in Figure 2 actually overestimate the international dissemination associated with a particular sensor. For example, of the 65 papers (Table 1) citing OCM data, only two have author lists without Indian affiliation. The follow-on to OCM, OCM-2, was launched in September 2009. A major impetus for OCM-2 was the need for ocean-colour data for forecasting potential fishing zones (PFZs; see Nayak et al., 2003). It is anticipated that data from OCM-2 will be more accessible to the international community, but this remains to be seen.

Europe launched the Medium Resolution Imaging Spectro-meter (MERIS) in 2002. MERIS has a narrower swathe width than SeaWiFS and MODIS and, hence, less frequent coverage. Although MERIS data accessibility has improved since its launch, there are still issues. For example, level 1 data, which are needed to apply regional atmospheric corrections, are not openly distributed. The more restricted data availability, relative to US sensors, is reflected in the statistics on MERIS publications, which are predominantly European (Figure 2) and relatively few, given the time in orbit (Table 1).

Future ocean-colour sensors and potential problems for the research community

The first US ocean-colour sensor to be launched as an operational mission will be the Visible/Infrared Imager Radiometer Suite (VIIRS) in 2012. VIIRS was developed as part of the National Polar-orbiting Operational Environmental Satellite (NPOESS) programme, designed to meet the requirements of NASA, NOAA, and the US Department of Defense. However, in February 2010, because of cost overruns, NPOESS was restructured into the Joint Polar Satellite System (JPSS), a programme to be run jointly by

Table 1. Number of publications citing the different ocean-colour sensors, the number of publications per year the satellite was in orbit, and the number of papers with a subject classification of "oceanography" or "fisheries", or with "fish" included in the search string.

			Oceanography		Fisheries		"Fish" in search	
Sensor[a]	Number of papers	Papers per orbit year	Number	%	Number	%	Number	%
CZCS	428	56	208	49	7	2	8	2
GLI	34	49	11	32	0	0	0	0
SeaWiFS	1 175	92	478	41	24	2	32	3
MERIS[a]	140	17	14	10	0	0	2	1
MODIS[a]	361	45	74	20	4	1	3	1
OCM[a]	65	6	19	29	0	0	8	12
OCTS[a]	64	80	17	27	0	0	1	2
Total	2 267	46	821	36	35	2	54	2

[a]Search string included the term "colour" ("color") or "chlorophyll".
As of 19 May 2010. Source: ISI Web of Science.

Country affiliations associated with publications citing various ocean-colour sensors
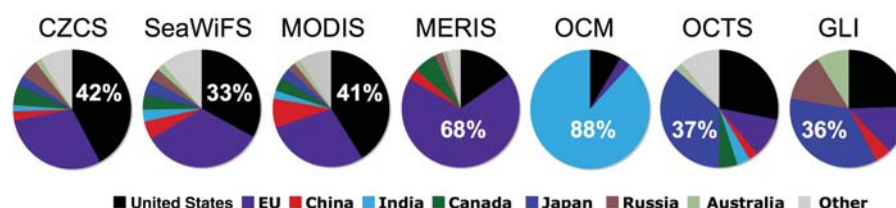
Figure 2. Distribution of the country affiliations associated with publications citing the CZCS, SeaWiFS, MODIS, MERIS, OCM, OCTS, and GLI ocean-colour sensors. The percentage of publications from the country that launched the satellite is displayed (as of 19 May 2010. *Source*: ISI Web of Science).

NOAA and NASA. The first satellite scheduled to be launched under NPOESS was a precursor satellite called the NPOESS Preparatory Project (NPP), whose name has not changed despite the program restructuring. Hence, the first VIIRS sensor will be launched on the NPP satellite, scheduled for 2012. The first two JPSS satellites, currently scheduled for launch in 2016 and 2019, will also carry a VIIRS sensor (Figure 1).

If either MODIS or MERIS, both past their design life, fails before the launch of NPP in 2012, there will be a gap in the continuity of the climate data record (CDR) for global ocean-colour data [a CDR has been defined as a time-series of measurements of sufficient length, consistency, and continuity to determine climate variability and change (National Research Council, 2004)]. Beyond the data-continuity problem is the inability to calibrate between different sensors, prohibiting incorporation of future ocean-colour datastreams into the current continuous stream extending back to 1997.

Additional technical issues with VIIRS preclude a CDR from NPP, although these should be resolved for the VIIRS sensors on JPSS-1 and JPSS-2. If the currently operating ocean-colour sensors fail before the launch of VIIRS, the availability of data from the OCM-2 will be critical (Figure 1). Europe is planning to launch the Ocean Land Colour Instrument (OLCI) in 2013 and Japan plans to launch the Second-Generation Global Imager (SGLI) in 2014 (Figure 1). Both launches are planned after VIIRS on NPP; therefore, they will not mitigate any gap before VIIRS/NPP, but they could provide critical information if data from VIIRS/NPP are not of sufficient quality.

The above ocean-colour sensors all have different numbers of spectral bands, spatial resolutions, repeat times, and degrees of calibration, which complicate data comparison between them (Maritorena and Siegel, 2005; Morel *et al.*, 2007; D'Alimonte *et al.*, 2008; Gregg and Casey, 2010). For example, SeaWiFS and MODIS, although processed with consistent methods, have significant differences that must be resolved before merging their datastreams into one record (Franz *et al.*, 2005; Gregg and Casey, 2007, 2010). An in-depth comparison of the different sensors is beyond the scope of this paper; detail can be found elsewhere (Gregg *et al.*, 1998; Franz *et al.*, 2005; Lee *et al.*, 2007a; Gower *et al.*, 2008; McClain, 2009; Djavidnia *et al.*, 2010).

Importance of ocean colour to research

The advent of satellite ocean-colour data transformed the field of biological oceanography. More than 2000 papers have been published using ocean-colour data (Table 1). In addition to a number of review articles summarizing the research impact of satellite ocean-colour data (McClain *et al.*, 2006; Yoder and Kennelly, 2006; McClain, 2009), there have been a number of special volumes devoted to ocean-colour results (Barale and Schlittenhardt, 1993; Mitchell, 1994; Siegel *et al.*, 2004a, b). Some specific contributions resulting from analysis of ocean-colour data include (in no particular order):

(i) refining our understanding of the seasonal cycles of surface-ocean chlorophyll (Yoder *et al.*, 1993; Longhurst, 1995, 2007);

(ii) defining ecological provinces in the ocean (Longhurst, 1995, 2007; Platt and Sathyendranath, 1999; Spalding *et al.*, 2007; Devred *et al.*, 2007);

(iii) determining interannual variations in the seasonal cycle of chlorophyll (Vargas *et al.*, 2009);

(iv) quantifying the phenological match between commercially important species and their planktonic food (Platt *et al.*, 2003; Koeller *et al.*, 2009a);

(v) identifying specific types of phytoplankton, such as coccolithophorids (Brown and Yoder, 1994; Gordon *et al.*, 2001), *Trichodesmium* (Borstad *et al.*, 1992; Subramaniam *et al.*, 2002; Westberry and Siegel, 2006), or different phytoplankton functional types (Sathyendranath *et al.*, 2004; Alvain *et al.*, 2008);

(vi) detecting and monitoring harmful algal blooms (HABs; Stumpf, 2001; Allen *et al.*, 2008; Hu *et al.*, 2008);

(vii) mapping river plumes (Hochman *et al.*, 1994; Hu *et al.*, 2004);

(viii) examining upwelling dynamics (Thomas *et al.*, 2001; Campillo-Campbell and Gordoa, 2004; Garcia *et al.*, 2008);

(ix) quantifying the basin-scale impact of *El Niño* events (Chavez *et al.*, 1999; Wilson and Adamec, 2001; McClain *et al.*, 2002; Sackmann *et al.*, 2004);

(x) depicting long-terms trends in global patterns of chlorophyll (Gregg and Conkright, 2002; Dandonneau *et al.*, 2004; Gregg *et al.*, 2005; Polovina *et al.*, 2008; Martinez *et al.*, 2009; Vantrepotte and Melin, 2009);

(xi) determining how variability of the penetration of solar radiation into the ocean surface affects circulation, mixing, and

climate (Lewis *et al.*, 1990; Sweeney *et al.*, 2005; Wetzel *et al.*, 2006; Anderson *et al.*, 2007; Gnanadesikan and Anderson, 2009);

(xii) improving biological and ecological models through either data assimilation or validation (Fan and Lv, 2009; Fontana *et al.*, 2009; Jolliff *et al.*, 2009; Ourmieres *et al.*, 2009);

(xiii) determining ocean primary productivity (Behrenfeld and Falkowski, 1997; Campbell *et al.*, 2002; Carr *et al.*, 2006);

(xiv) mapping coloured dissolved organic matter (CDOM) distributions (Siegel *et al.*, 2005); and

(xv) identifying anomalous chlorophyll blooms (Uz, 2007; Wilson and Qiu, 2008).

These research applications provide basic information about marine ecosystems. However, most of them do not have a direct operational component. Usages of ocean-colour data in the management of fisheries and aquaculture, and other societal benefits of ocean-colour data, were recently reviewed in two reports from the International Ocean Colour Coordination Group (IOCCG, 2008, 2009) and are summarized below.

Operational uses of ocean colour

The definition of "operational" varies widely depending on the application or the community in question. The primary use of operational satellite data products has been weather forecasting, an application that requires access to near-real-time (NRT) data-streams, 24 h a day, 7 d a week (24/7). Hence, there is a misconception that operational uses always require NRT, 24/7 data. However, for fishery management, an interannual climate quality datastream is often more relevant. Another definition used within the R2O context interprets the term operational as encompassing anything not research, which is very ambiguous. NOAA's policy on R2O (NOAA, 2008) defines operations as "sustained, systematic, reliable, and robust mission activities with an institutional commitment to deliver appropriate, cost-effective products and services". NOAA's mission includes mitigating coastal hazards, sustaining marine ecosystems, and monitoring climate variations. By this definition, the integration of ocean-colour data into activities supporting those mission objectives should constitute an operational use. However, it is not clear how widely this is accepted. Although the issue of what is operational might seem semantic, it is clearly important to the justification of new missions.

Harmful algal blooms

Monitoring HABs is one example of a clear R2O transition of ocean-colour data. Toxin-producing algae that have negative impacts on humans, marine organisms, and/or coastal economies, HABs can result in the closure of shellfish beds and beaches, massive fish kills, illness and death to marine mammals and sea-birds, and alteration of marine habitats. Consequently, HAB events adversely affect commercial and recreational fishing, tourism, and valued habitats, creating a significant impact on local economies and the livelihood of coastal residents. Advanced warnings of HAB events and estimation of their spatial distributions increase the options for managing such events and minimizing their harmful impact.

The large spatial scale and high frequency of observations needed to assess bloom location and movements make ocean-colour satellite data a key component in HAB research and

forecasting. New blooms can be identified by a chlorophyll-anomaly method that accounts for the complex optical properties in coastal waters that can confound the satellite chlorophyll algorithm (Stumpf *et al.*, 2003a; Tomlinson *et al.*, 2009). For some coastal waters with large quantities of organic matter, fluorescence data from the MODIS and MERIS sensors have the potential of providing better estimates of bloom extent (Hu *et al.*, 2005; Zhao *et al.*, 2010).

Limitations of satellite HAB research and forecasting include the need for *in situ* water sampling, because not all high-chlorophyll features are HABs. There are also many different types of HAB, and algorithms developed for one species and region often are not transferable. Additionally, not all HABs can be detected by satellite ocean-colour data (Anderson, 2009), and the spatial resolution of the current ocean-colour sensors can be too coarse to detect features in many of the coastal regions where HABs develop. Despite these limitations, satellite ocean colour can be an effective tool for monitoring HABs, which NOAA has done operationally in the United States since 2006, producing HAB bulletins twice a week for the Gulf of Mexico (Stumpf *et al.*, 2009). Ocean-colour-based operational HAB forecasts are also under development in Europe (Johannessen *et al.*, 2006) and Australia (Roelfsema *et al.*, 2006).

Fisheries

In the broadest sense, fisheries encompass not just commercially important fish stocks, but all living marine resources (LMRs), including threatened and endangered species of fish, as well as marine mammals and invertebrates. There are three distinct aspects of fisheries, harvesting, assessment, and management, all of which have different goals. Satellite ocean-colour data have been used extensively to help harvest fish more efficiently in India and Japan (Wilson *et al.*, 2008; Saitoh *et al.*, 2009). Although this is a clear operational use of the data by some definitions (Kendall and Duker, 1998), it is not applicable for NOAA, because improving harvesting efforts is not part of its mandate to manage and conserve LMRs. Consequently, the agency cannot provide services, such as the PFZ maps distributed by the Indian government (Nayak *et al.*, 2003; Choudhury *et al.*, 2007), or compete with those available commercially (Saitoh *et al.*, 2009, 2011). Hence, for NOAA, operational usages of ocean colour in a fisheries context refer to those that involve the assessment or management of LMRs.

Assessment and management of exploited species

The primary operation within NOAA Fisheries is stock assessment. NOAA is responsible for managing more than 900 commercially important stocks and ~210 protected or endangered species (National Marine Fisheries Service, 2001). Assessments provide the technical basis for setting annual fish quotas and other management measures to achieve optimum yield and concurrently avoiding overfishing and ecosystem harm. At a minimum, a quantitative stock assessment requires monitoring of catch, abundance, and biological characteristics of the stock. Achieving a balance between exploitation and conservation requires substantial information about the stock, its fishery, the ecosystem, and the habitat; however, data on the last two have seldom been incorporated into stock assessments. The environmental factors influencing populations are complex and poorly understood, so they have largely been excluded from traditional assessment models, which greatly limits their

accuracy and effectiveness (Koeller *et al.*, 2009b). Bringing environmental and ecological data into the process requires radical changes to the overall management approach, including the adoption of conceptual and analytical frameworks that accommodate them—a daunting prospect counter to the conservative nature of fisheries assessment and management.

Recently, there has been a move towards ecosystem-based management of fisheries (Browman and Stergiou, 2005; Sherman *et al.*, 2005; Frid *et al.*, 2006), which has given new impetus to a better understanding of the environmental factors influencing fish stock dynamics and to include environmental variability as an integral part of the assessment process. Most of the spatial features that characterize ecosystems and ecosystem variability, i.e. ocean fronts, eddies, convergence zones, and river plumes, cannot be resolved adequately without satellite data. The measurements of primary productivity and chlorophyll obtained from satellite ocean-colour data greatly facilitate monitoring the base of the oceanic food chain, and these parameters form part of the assessment strategy for large marine ecosystems (LMEs; Sherman and Hempel, 2008; Chassot *et al.*, 2011; Sherman *et al.*, 2011).

Management of protected species

Satellite ocean-colour data provide key information about the oceanographic conditions associated with the distribution and migration patterns of protected species. For example, satellite ocean-colour data allow the tracking of seasonal and interannual variations of the transition zone chlorophyll front (TZCF), a boundary in the North Pacific separating cool, high-chlorophyll, vertically mixed water in the north, and warm, low-chlorophyll, vertically stratified subtropical water in the south (Polovina *et al.*, 2001). The TZCF is an important migration pathway for endangered loggerhead turtles (*Caretta caretta*) that forage in the high-chlorophyll, meandering eddies associated with the front (Polovina *et al.*, 2004; Kobayashi *et al.*, 2011). Other apex predators, such as albacore tuna (*Thunnus alalunga*), also use the front as a migratory corridor (Laurs and Lynn, 1977; Polovina *et al.*, 2001). The extent of meandering of the TZCF appears to influence trophic transfers and productivity, with more meandering resulting in higher catch per unit effort of albacore (Polovina *et al.*, 2001). Interannual variability of the southern extent of the TZCF also affects the survival of juvenile monk seals (*Monachus schauinslandi*) in the Hawaiian islands (Baker *et al.*, 2007).

The types of information described above provide the framework upon which to build ecosystem-based management strategies. For example, a NOAA programme called TurtleWatch uses satellite ocean-colour data, in part, to predict areas with a high probability of loggerheads and longline interactions, so that fishers can minimize turtle bycatch (Howell *et al.*, 2008). For monk seals, satellite ocean-colour data can be used to predict years when low survival is likely and, hence, when management intervention, such as a head-start programme, should be implemented (Wilson *et al.*, 2009). Ocean-colour data are also being used to predict the movement and congregation of highly endangered northern right whales (*Eubalaena glacialis*) in the Atlantic, with the management aim of mitigating their ship-strike mortality (Pershing *et al.*, 2009).

Why are satellite ocean-colour data underutilized in fisheries?

Despite these uses, it can be argued that the full potential of satellite ocean-colour data has not been realized within NOAA or in fisheries science generally. For example, <2% of the publications using ocean-colour data have involved any aspect of fisheries (Table 1). Perhaps the small number of fisheries-related publications is because of the exclusion of stock assessment papers to the grey literature, but this seems unlikely, given the paucity of environmental data in stock assessments generally (Koeller *et al.*, 2009b). The small number could also be an artefact of insufficient classification within the citation database. The numbers are based on citations with "fisheries" listed as the subject, so papers dealing with protected species are mostly excluded. Note also that just 35% of the ocean-colour papers are classified under "oceanography" (Table 1), yet one would expect the majority using ocean-colour data to have an oceanographic basis. Including "fish" in the search string resulted in a few more papers, but did not change the overall result. The relatively high percentage (12%) of OCM papers dealing with fish reflects the use of these data in the Indian PFZ programme (Nayak *et al.*, 2003; Choudhury *et al.*, 2007). Nonetheless, Table 1 supports the assertion that ocean-colour data are largely underutilized in fisheries science. There may be several reasons for this.

(i) *Dissemination.* Satellite data availability and their potential use in fisheries are not always effectively communicated outside the satellite community.

(ii) *Unfamiliarity.* Satellite data can be difficult to access, manipulate, and process, particularly when the skills and computational resources needed for manipulating large datasets are lacking.

(iii) *Unavailability of desired products.* For many fisheries applications, the parameter of interest may not be readily available or easily calculated. Examples of these include primary production, front locations, and climatologies.

(iv) *Data inadequacy.* The 12-year time-series of ocean-colour data is relatively short compared with fisheries datasets that often span many decades. Additionally, many fisheries operate in coastal (case II) waters, where interpretation of satellite ocean colour is complicated by the lack of site-specific algorithms—the standard algorithms are defined for open-ocean (case I) waters (Gordon and Morel, 1983).

(v) *Resistance to change.* Stock assessment/management tends to avoid the use of environmental data, because of the complexities involved, especially when simpler population models often suffice for short-term (∼1 year) predictions. For assessment biologists, it can also be difficult or impossible to undertake new and innovative analyses in addition to preparing routine assessments built on traditional frameworks.

What can be done?

Some of the issues listed above are easier to address than others. The first three, involving data distribution and usage, are relatively straightforward, compared with ensuring data continuity, better

characterization of coastal waters, or changing stock assessment methodologies.

Training

Satellite data literacy can be enhanced through training courses specifically designed for target audiences, such as marine resource managers. The IOCCG has a strong interest in capacity building and has, since 1997, been conducting and sponsoring courses on the usage and application of ocean-colour data in various developing countries. For example, the symposium covered by this issue included a training session attended by 55 trainees from 16 countries. NOAA has also held several satellite courses for its scientists since 2006. Such courses are particularly helpful when both data providers and data users are involved. In addition to educating participants about the availability, access, and use of satellite data, providers obtain a better understanding of user needs and requirements. Some examples of this are given below.

Better data accessibility

Courses conducted by NOAA were designed to help participants work with satellite data using ArcGIS, software familiar to many fishery scientists. Because importing satellite data into ArcGIS can be cumbersome, particularly for lengthy time-series, a new ArcGIS extension (Environmental Data Connector, EDC) now allows users to browse and subset large amounts of data online and convert them into raster or feature classes. The EDC also facilitates users animating and manipulating data for temporal analysis, including provision for non-uniform time-steps. A new version under development will allow access to sensor data served by protocols compliant with IOOS (Integrated Ocean Observing System). The EDC is available, at no cost, at http://www.pfeg.noaa.gov/products/EDC/ or http://www.asascience.com/.

NOAA courses also identified the need for a simple method of matching satellite data with moving datapoints, such as tagged animals or ships. Navigating global satellite datasets for the few values associated with a telemetry track can be daunting. To alleviate this problem, open-access routines were developed using either Matlab or R (freeware). These "xtractomatic" extraction routines take advantage of the effective data-delivery mechanisms provided by THREDDS (Thematic Real-time Environmental Distributed Data System) catalogues and perform extractions based on the input of longitude, latitude, time, and a chosen variable (SSH, SST, chlorophyll, etc.). These routines are freely available at http://coastwatch.pfel.noaa.gov/xtracto/.

In the past 5 years, web-based methods of accessing and visualizing different satellite data products have increased dramatically. It is no longer sufficient to simply post large datafiles on the web and expect them to be used. For example, NASA's Giovanni system allows online visualization and analysis of ocean-colour data, including views of climatologies or anomalies (http://reason.gsfc.nasa.gov/Giovanni/). Primary productivity products are now available online (at http://www.science.oregonstate.edu/ocean.productivity/ and http://coastwatch.pfel.noaa.gov/coastwatch/CWBrowserWW360.jsp). Ocean-colour data are often just one of many satellite products of interest, so sites that offer one-stop shopping are most useful. For example, a comprehensive collection of environmental satellite data products (including primary productivity and front locations) is available at NOAA's west coast Coastwatch site (http://coastwatch.pfel.noaa.gov/coastwatch/CWBrowserWW360.jsp).

Improving data coverage temporally and spatially

Coastal waters contain most of the world's fisheries, but they also contain CDOM and sediments that confound the chlorophyll algorithms designed for open waters without these constituents (IOCCG, 2000). Additionally, different atmospheric corrections are required for accurate characterization of case II waters (Land and Haigh, 1996; Stumpf et al., 2003b; Schroeder et al., 2007). Although improvements have been made in the chlorophyll algorithms for coastal waters from the current sensors (Gitelson et al., 2009; Komick et al., 2009; Kuchinke et al., 2009; Moses et al., 2009), these studies are all region-specific, as are the algorithms. To address this issue on a global scale, Europe recently established the CoastColour project, which will develop and validate different case II algorithms for the MERIS instrument over a global range of coastal water types.

Coastal zones are extremely dynamic relative to the open ocean, so greater spatial and temporal resolution is needed to resolve their features, e.g. 30–300 m, multiple looks per day (IOCCG, 2000). These spatial and temporal scales are unachievable simultaneously with polar-orbiting satellites. Airborne sensors deliver high spatial resolution, with fewer atmospheric correction issues, but provide only a single snapshot in time (Carder et al., 1993; Davis et al., 2002; Filippi et al., 2006). Geostationary satellites are the best option for high temporal resolution, which has been demonstrated with SST data (Maturi et al., 2008). The first ocean-colour sensor on a geostationary satellite was launched by South Korea in July 2010 (Neukermans et al., 2009; Lee et al., 2010). Additionally, there is increasing interest in satellite or airborne hyperspectral sensors to characterize coastal waters better (Malthus and Mumby, 2003; Brasseur et al., 2009). For example, data from Hyperion, a NASA hyperspectral sensor originally designed for land applications, have been useful in complex coastal regions (Brando and Dekker, 2003; Lee et al., 2007b).

It is crucial that CDRs of ocean-colour data be archived and maintained to provide a baseline for gauging marine ecosystem change and to track historical variations. Clearly, development and maintenance of global coverage requires an international effort, and considerable progress has been made. For example, the Committee on Earth Observation Satellites (CEOS) developed the concept of satellite constellations providing virtual global coverage. The implementation plan for the Ocean-Colour Radiometry Virtual Constellation (OCR–VC) is being developed by a working group of the IOCCG (Yoder et al., 2009). The European GlobColour project currently generates a consistently calibrated global product with the best possible spatial coverage, by merging ocean-colour data from SeaWiFS, MODIS, and MERIS (Pinnock et al., 2007).

Shifting paradigms

Although traditional stock assessments do not usually incorporate environmental variability, there is growing interest in ecosystem-based management strategies (Sherman et al., 2005; Frid et al., 2006). Satellite chlorophyll measurements are a basic component in the definition and assessment of LMEs (Sherman et al., 2011) and the development of an ecosystem approach to fisheries (EAF; Chassot et al., 2011). Integrated ecosystem assessments (IEAs) with appropriate ecosystem indicators, including satellite observations, have been proposed as a framework for ecosystem-based management (Levin et al., 2009). Although there is much uncertainty and controversy surrounding ecosystem indicators,

there is general agreement that they should be directly observable, supported by historical time-series and understandable by the general public (Rice and Rochet, 2005; Levin *et al.*, 2009). These important criteria are all applicable to satellite ocean-colour data.

Concluding remarks

The research value of satellite ocean-colour data is substantial and they have become indispensible for many marine research applications. The value of satellite ocean-colour data for better understanding the oceans, which cover 71% of our planet, and monitoring interannual changes in marine ecosystems is compelling enough to require a sustained datastream of global ocean-colour data.

(i) Ocean-colour data are used operationally in the monitoring of HABs and in fish finding-type programmes (India, Japan).

(ii) The relevant time-scales for operational usages of ocean-colour data in fisheries assessment and management are seasonal and interannual, so they require a continuous time-series of science-quality, ocean-colour data.

(iii) Ocean-colour data are needed in the assessments of marine habitats and ecosystems and to monitor climate variability. Currently, many of the capabilities of ocean-colour data are still being researched actively and have not yet transitioned into management strategies.

(iv) It would be unfortunate if another gap in ocean-colour data developed, so prohibiting the merger of the current 12-year record with future ocean-colour data.

Acknowledgements

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